

Model Development for Predicting Rigid Body Movement in Air-Water-Sediment Columns with Fast Water Entry (STRIKE35)

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LONG-TERM GOAL

The long-term goal of this project is to improve warhead lethality for use in quick, precise and accurate strikes on known enemy naval minefields in the littoral combat environment.

To do so, the Bomb Maneuvering Model for Obstacle Clearance (i.e., STRIKE35) has been developed to predict the bomb movement and orientation in air, water, and sediment columns during an amphibious assault. General-purpose bombs such as MK-84 represent an existing and rapidly deployable building block for developing an effective system against obstacles (or mines). STRIKE35 is developed on the base of fluid dynamics, fluids engineering and fluid-structure interaction. It predicts the bomb tracks leading to the primary goal of the Bomb Effects program which is to provide technology the Department of Navy and the Marine Corps can use to efficiently conduct obstacle clearance in support of an amphibious assault. Furthermore, the NPS students (U.S. military officers) work on STRIKE35 as their thesis studies that enhance the Navy's R&D program and well prepare the students with their combat effectiveness.

OBJECTIVES

The objectives in FY06 were:

- To improve 6 degrees of freedom (DOF) model (STRIKE35) for predicting bomb (high-speed rigid body) maneuvering in the air-water-sediment columns
- To analyze the data from the bomb strike experiments
- To use the noise filtering method (i.e., the rotation method) to process the data collected from the bomb strike experiments
- To determine the drag and lift coefficients for MK-84 bomb using the inverse method
- To integrate the NPS effort on bomb effect for mine clearance into the Naval Oceanographic Office mine warfare program for operational use

APPROACH AND RESULTS

(A) Model Structure and Core Physics

STRIKE35 contains several important components such as (a) 6 DOF fast moving rigid body model using triple-coordinate systems, (b) fast water impact, (c) fluid flow model for supercavitation and drag-lift coefficients, and (d) water-sediment cavity (Fig. 1).

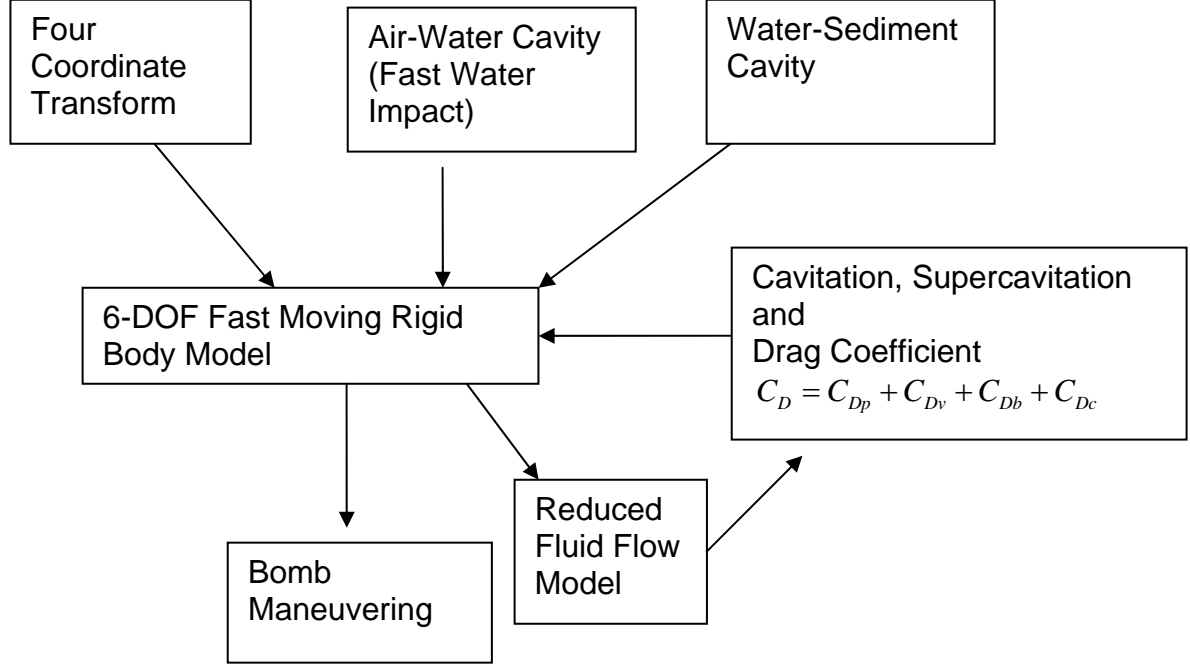


Fig. 1. Structure of STRIKE35 for predicting bomb maneuvering.

The 6-DOF fast moving rigid body is described by

$$\frac{d}{dt} \begin{bmatrix} u \\ v \\ w \end{bmatrix} = - \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} + \frac{\mathbf{F}_b + \mathbf{F}_h(C_D, C_{L_i}, u, v, w, u_w, v_w, w_w)}{\rho \Pi}, \quad (1)$$

$$\mathbf{J} \cdot \frac{d\boldsymbol{\omega}}{dt} = \mathbf{M}_b + \mathbf{M}_h(C_D, C_{L_i}, u, v, w, u_w, v_w, w_w), \quad (2)$$

where g is the gravitational acceleration; $\mathbf{V} = (u, v, w)$ is the velocity of the bomb; $\mathbf{V}_w = (u_w, v_w, w_w)$ is the water velocity; Π is the volume of bomb; ρ is the density; $\rho \Pi = m$, is the mass; $\mathbf{F}_b (= \rho_w \Pi g)$ is the buoyancy force; \mathbf{F}_h is the hydrodynamic force (i.e., surface force including drag, lift, impact forces); ρ_w is the water density; $(\mathbf{M}_h, \mathbf{M}_b)$ are moments due to the and buoyancy forces; $\boldsymbol{\omega}$ is the angular velocity vector; \mathbf{J} is moment of gyration tensor. Using the four coordinate transform (new development), the moment of gyration tensor has only three scalar components, and the

hydrodynamic force and torque are easy to compute. The hydrodynamic force (F_h) and torque (M_h) depend on the coefficients (C_D , C_l) and relative velocity of bomb to water (following the drag and lift laws).

(B) NPS Bomb Strike Experiment

We conducted a bomb strike experiment with four shapes (Mk-84, Mk-84 without fin, capsule, and cylinder) at the Monterey Bay Aquarium Research Institute (MBARI) Unmanned Underwater Vehicle Test Tank (Figure 2). Enclosed inside a large building, this 10 m×15 m×10 m tank was filled with “standard sea water.” This water was maintained by an ozone filtration system, with no impurities save the remnants of blue dye placed into the tank several weeks prior to the experiment. The faint blue coloration had no effect on the shape trajectories, but it did add some difficulty illuminating the tank. Hence the video data quality was somewhat degraded. A sliding bridge, on which the slanted board was mounted, spanned the width of the tank. Figure 2b describes the measurements of the tank and placement of the strike zone, cameras, and lighting.

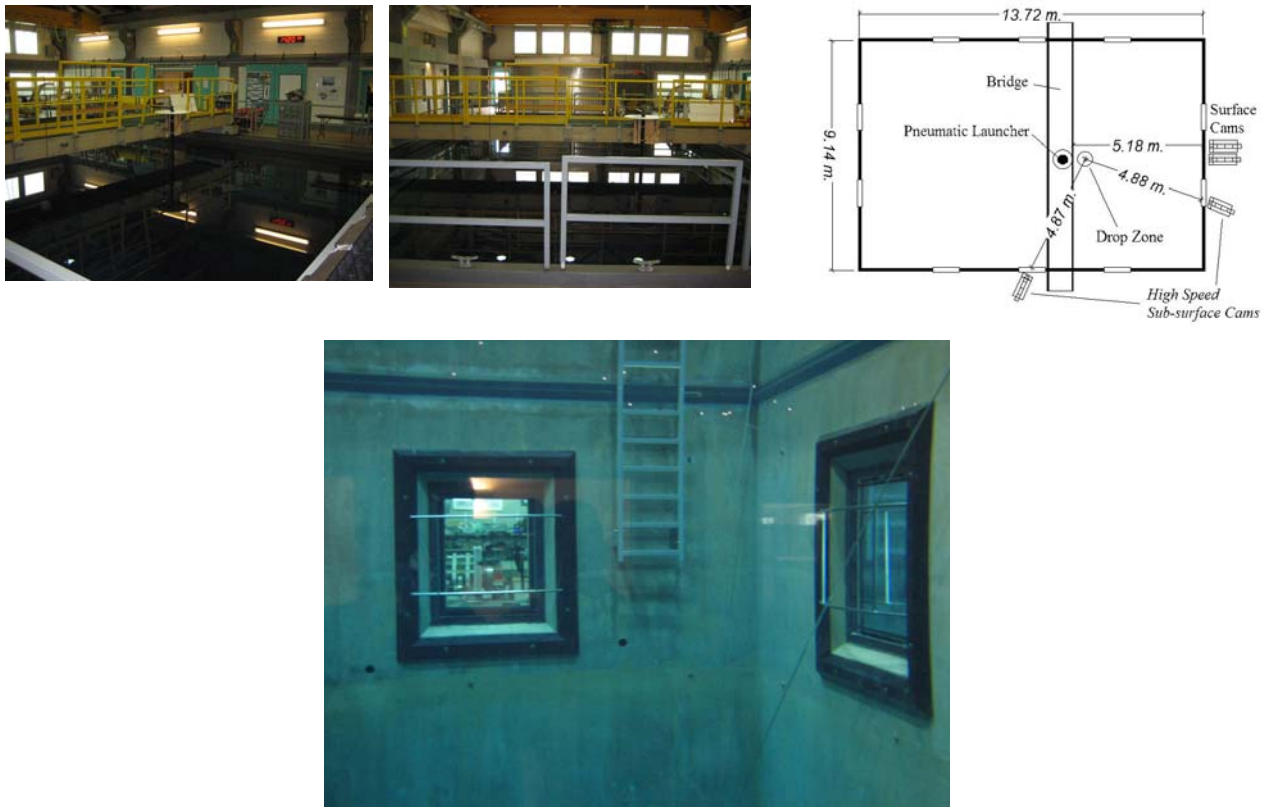


Figure 2. (a) MBARI Test Tank Facility (structure above water is moveable bridge), (b) top view of MIDEX-II setup, (c) side view of the tank.

The MK-84 general purpose bomb was chosen as the prototype for modeling due to its current employment in the JDAM Assault Breaching System (JABS) (Almquist, 2004, 2005). Thus, we use right-cylinder, right-cylinder with hemispheric nose cone (capsule), 1/12 scale model of the MK-84 GP munitions (bomb) and a modified version of the Mk-84 bomb which had no stabilizing fins (shell). The construction of the test shapes consisted of a three part production process: prototype development, mold construction and test shape casting and finishing. This process was

necessary to facilitate more efficient experimentation and to reduce the production cost of the experimental test shapes (Figure 3). Final prototypes with dimensions are depicted in Figure 4 and Table 1.

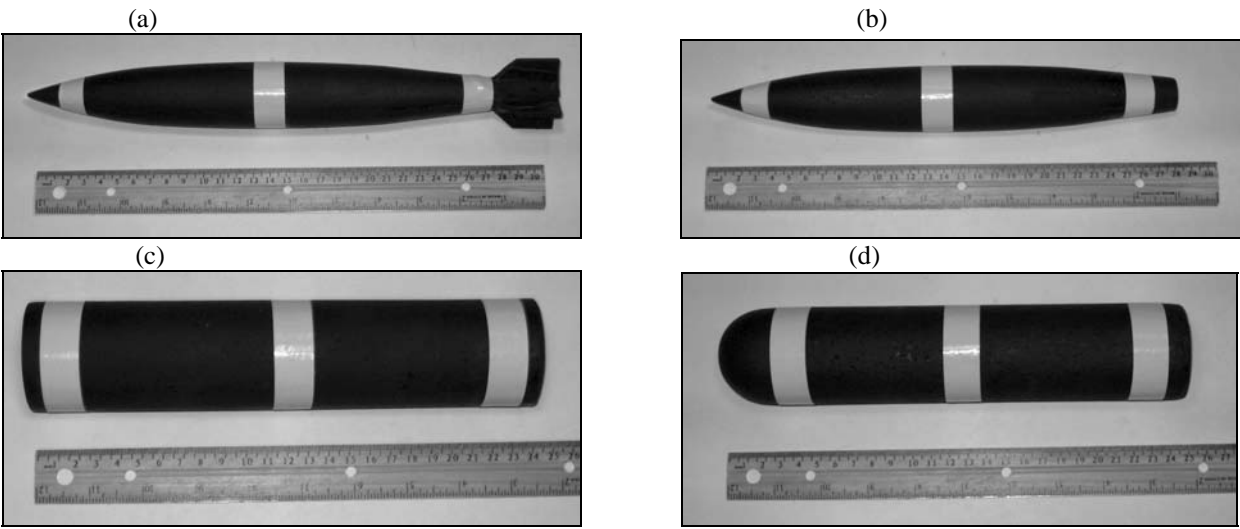


Figure 3. (a) MK-84 bomb models with 1/12 scale, (b) shell test model, (c) cylinder test model, and (d) capsule test model.

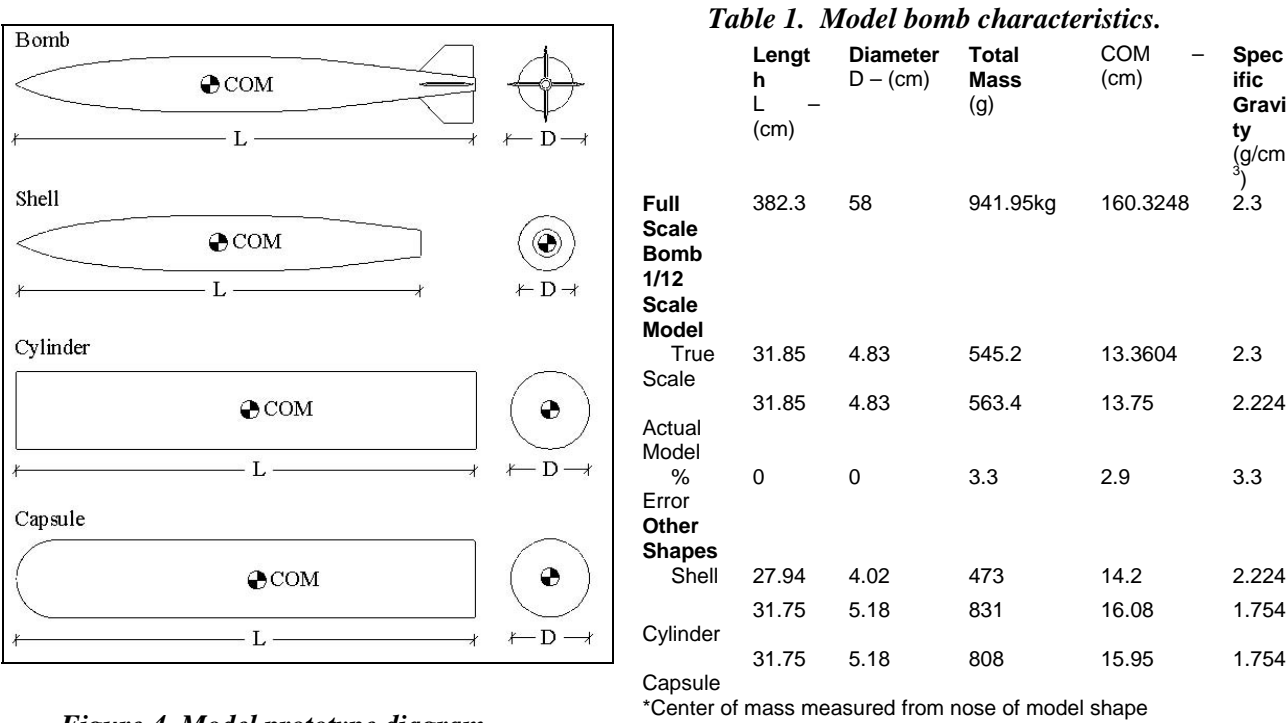


Figure 4. Model prototype diagram.

The model bombs were launched vertically by pneumatic launcher with about 100 m/s velocity into the water. The entry of each shape into the water was recorded by the two above surface video cameras. This above-surface data was then digitally analyzed using 2-D motion analysis software to determine the initial velocity of all shapes. All below-surface data collection was facilitated by the two FASTCAM PCI high-speed cameras. The below-surface digital data was analyzed by 3-D motion analysis software to determine the trajectories of each shape. All data from runs which involved malfunctions were discarded (Figure 5). The data retrieval and analysis

phase of the project was a multi-step process which employed various software applications and analysis techniques to produce the final data set. Figure 6 depicts the general steps in this process. The experimental phase yielded a total of 43 movie sets, each consisting of a pair trajectory movies produced from the two sub-surface high-speed cameras. Figure 7 depicts the bomb trajectories as viewed from the two near-orthogonal high-speed cameras.

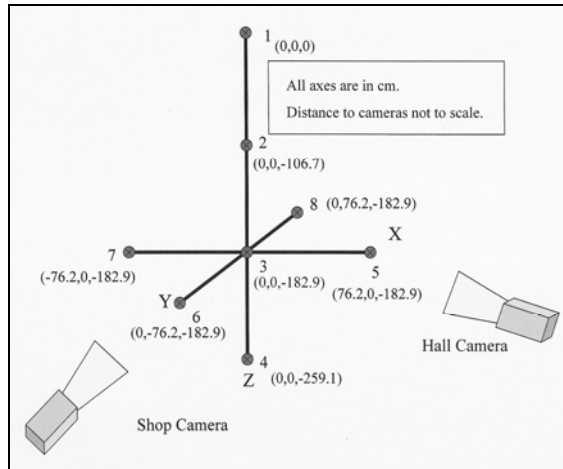


Figure 5. Underwater cameras.

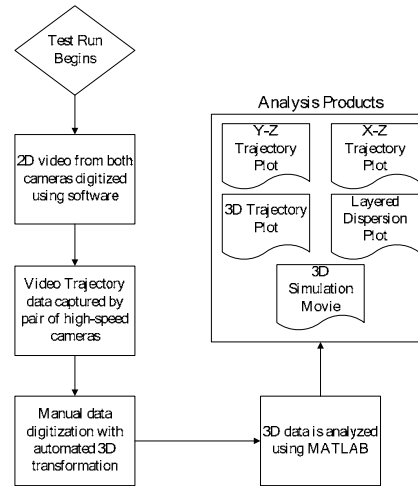


Figure 6. Data retrieval and analysis flow chart.

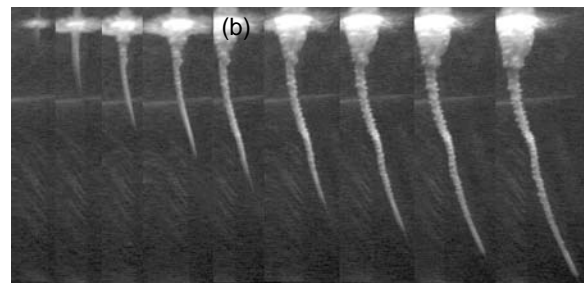
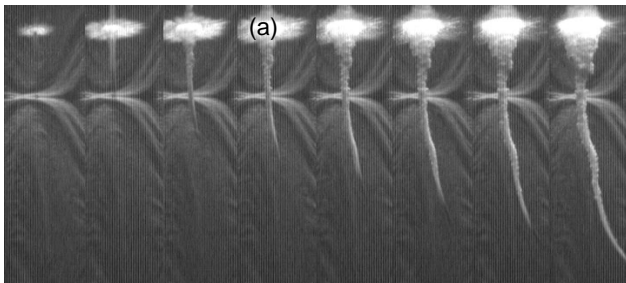


Figure 7. NPS model bomb trajectories from (a) Camera # 1, and (b) Camera #2.

(C) SRI Scaled Model Experiment

SRI International performed an experimental research program in which 1/12-scale high fidelity Mk84 bombs were launched into a deep-water pool at velocities of up to about 1000 ft/s (Gefken, 2006). Peter Chu and his students witnessed that experiment. Using two underwater high-speed video cameras, the underwater trajectory of the Mk84 bombs for a nominal vertical entry and for different possible tail configurations were determined. The different configurations included a complete warhead section with (1) a tail section and four fins, (2) a tail section and two fins, (3) a tail section and no fins, and (4) no tail section. These different tail configurations represent possible damage levels that may occur to the guidance tail section during water entry or because of tail slap within the cavitating region (Figure 8). Note that the basic features are very similar between high water entry velocity (around 300 m/s in the SRI experiments) and low water entry velocity (around 100 m/s in the NPS experiments).

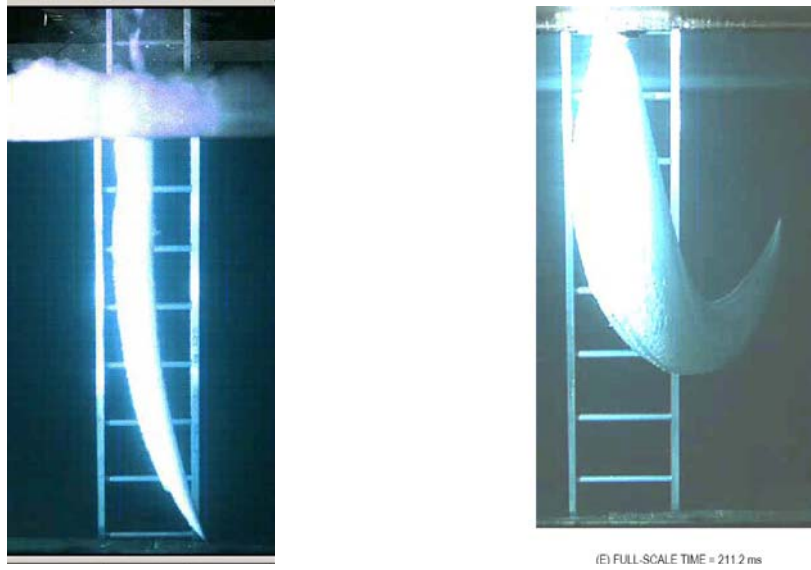


Figure 8. Examples of bomb trajectories from the SRI experiments.

(D) Data Analysis

The 3-D motion analysis software, MAXTRAQ, was the primary tool utilized to perform this function. Initially, the software was calibrated into the 3-D coordinate reference system utilizing the pairs of calibration images obtained in the initial phase of the experiment. Following calibration, both camera views were time synced and analyzed to determine the actual position of the shape in the x-y-z coordinate field. Frame-by-frame analysis was performed with the software for each view by manually identifying and input. Table-2 shows the sample data for Mk-84 model bomb. These data are ready for the bomb effect community to use.

Table 2. Examples of bomb maneuvering data

Bomb ID	Vintial	Time	pos(x)	pos(y)	pos(z)	Elevation	Azimuth
Shell05	109.4761	0	0	0	0	1.4455	1.6417
Shell05	109.4761	0.008	-5.5839	-7.1827	-76.6644	1.0169	-2.4077
Shell05	109.4761	0.016	-12.7976	-19.5688	-98.4973	0.1366	-2.1049
Shell05	109.4761	0.024	-17.3936	-26.2212	-104.6137	-0.8982	-2.0955
Shell05	109.4761	0.032	-19.4604	-31.7341	-106.7868	-1.3202	-2.6368
Shell05	109.4761	0.04	-21.1186	-36.1692	-108.4175	-1.278	2.0473
Shell05	109.4761	0.048	-22.2528	-38.3634	-109.289	-1.0945	1.5139
Shell05	109.4761	0.056	-23.1943	-39.5331	-109.0546	-1.0919	1.3989
Shell05	109.4761	0.064	-22.7167	-41.7202	-111.1178	-1.0598	1.2867
Shell05	109.4761	0.072	-24.3712	-41.6473	-110.1945	-1.0562	1.2861
...
...

(E) Determination of Coefficients (C_D , C_l) Using the Inverse Method

Most difficulty in STRIKE35 modeling is the uncertain coefficients (C_D , C_l). These coefficients change drastically during different stages of the fast moving body maneuvering such as impact, cavitation, supercavitation, etc. There is no existing data of (C_D , C_l) for bombs maneuvering in the water column. With the bomb trajectory data, the basic equations (1) and (2) are used to

optimally determine the drag and lift coefficients (C_D , C_l). For example, the drag and lift coefficients are expressed by

$$C_d = \begin{cases} 8.5 \frac{|\sin(2\alpha)| + 0.4}{Re^{1.5}} & \text{forward } \left(|\alpha| \leq \frac{\pi}{2}\right) \\ 4 \frac{|\sin(2\alpha)|}{Re^{1.5}} & \text{backward } \left(|\alpha| > \frac{\pi}{2}\right) \end{cases} \quad (3)$$

$$C_l = \begin{cases} 0.3 \cdot \sin(2\alpha) & \text{forward } \left(|\alpha| \leq \frac{\pi}{2}\right) \\ 0.12 \cdot \sin(2\alpha) & \text{backward } \left(|\alpha| > \frac{\pi}{2}\right) \end{cases} \quad (4)$$

from the SRI data. Here α is the attack angle (Figure 9). Re is the Reynolds number. The drag and lift forces are calculated by

$$f_{drag} = \frac{1}{2} C_d \rho^2 \pi R^2 V^2, \quad f_{lift} = \frac{1}{2} C_l \rho^2 D L V^2 \quad (5)$$

and the torque is calculated by

$$M = \sigma_f (f_{drag} \cdot \sin(\alpha) + f_{lift} \cdot \cos(\alpha)) \quad (6)$$

$$\frac{\sigma_f}{L} = \begin{cases} \frac{1}{60} (e^{9.7434(0.384-\alpha)} - e^{2.669(\alpha-0.384)}) & Re \geq 3 \cdot 10^7 \\ -0.3e^{-\frac{(Re/10^7-2.6)^2}{1.4369}} - 0.05 & Re < 3 \cdot 10^7 \end{cases} \quad \left(\frac{\sigma_f}{L} \leq \frac{1}{2}\right) \quad (7)$$

where L is the bomb length and R is the bomb radius. The semi-empirical formulas for the drag and lift coefficients (5)-(7) are verified by the data. Figures 10 and 11 show the dependence of C_D and C_l on Re and α and the comparison of (5)-(7) with the SRI data.

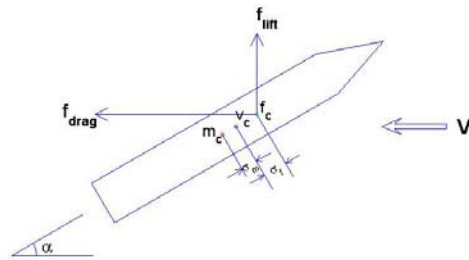


Figure 9. Dependence of the drag and lift coefficients on attack angle and Reynolds number.

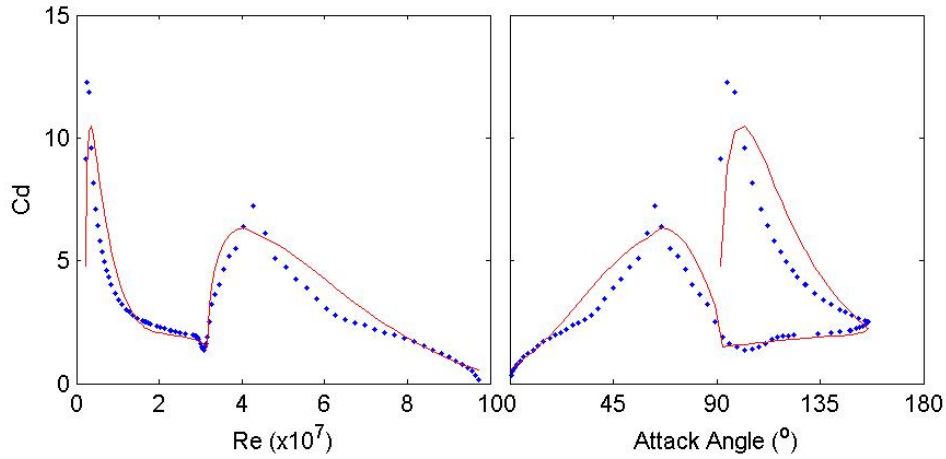


Figure 9. Dependence of C_D on Re and α with the red curve computed using (5)-(7) and the dots obtained from the SRI data.

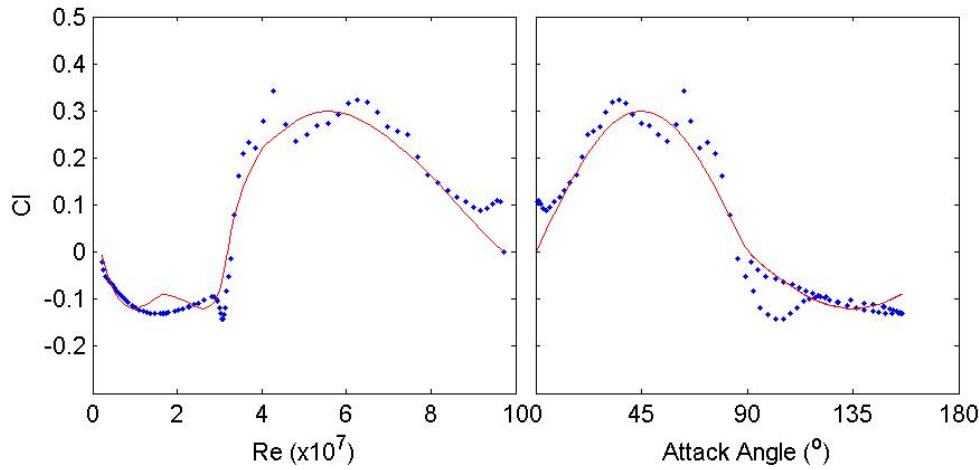


Figure 10. Dependence of C_L on Re and α with the red curve computed using (5)-(7) and the dots obtained from the SRI data.

- (2) Inverse method is proved an efficient method to determine the drag and lift coefficients of Manta and Rockan mines from the experimental data.

WORK COMPLETED

- Bomb strike experiment with four bomb shapes (Mk-84, MK-84 without fins, capsule, and cylinder) was conducted. Huge data about bomb maneuvering in water column were obtained.
- The experiment data went through thorough quality control procedures and stored as ascii files. It is very easy to be used by the community.

- The new schemes and formulas for computing drag and lift coefficients for Mk-84 bomb have been implemented and verified using the SRI experimental data.
- Four coordinate transform method was developed and evaluated. This method is the core of the hydrodynamic part of STRIKE35. The theoretical part of the method will be submitted to the Journal of Applied Mechanics.
- The comparison between STRIKE35 and SRI experiments has been conducted.
- The new results were published in Advances in Fluid Mechanics.
- The new results were presented in the Seventh International Symposium on Technology and Mine Problems, NPS, Monterey, California, May 1-4, 2006, and the International Symposium on Advances in Fluid Mechanics, Skiathos, Greece, May 8-10, 2006.

IMPACT/APPLICATIONS

- The dynamic system (nonlinear equations) for the bomb movement has the potential impact on the nonlinear dynamics. The hydrodynamics of bomb impact in water column can be applied to a general scientific problem of the fluid-rigid body interaction including stability and chaotic motion.
- The non-cylinder parameterization scheme will impact the scientific and Naval mine warfare communities on the movement of non-cylindrical mines in the water column.
- The inverse method for determining drag and lift coefficients for Mk-84 bomb from bomb strike experiments can be applied to general mechanical and aerodynamical engineering problems.

RELATED PROJECTS

This project is related to the ONR Mine Breaching Technology, and NAVOCEANO's Mine Warfare Programs. The results obtained from this project contributes to these programs.

THESES DIRECTED

Greg Ray, Bomb strike experiments for mine countermeasure, MS in Meteorology and Oceanography, March 2006

TRANSITIONS

- The results obtained from this project are transferred to the Naval Oceanographic Office, COMINWARCOM, and the ONR Bomb Effect group.
- The bomb maneuvering dataset in the water column collected at the NPS-Bomb-Strike Experiment is ready for the community to use.
- The semi-empirical formulas of (C_D, C_l) for Mk-84 can be used by the bomb effect group.

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